Energy Recovery Linac

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Outline

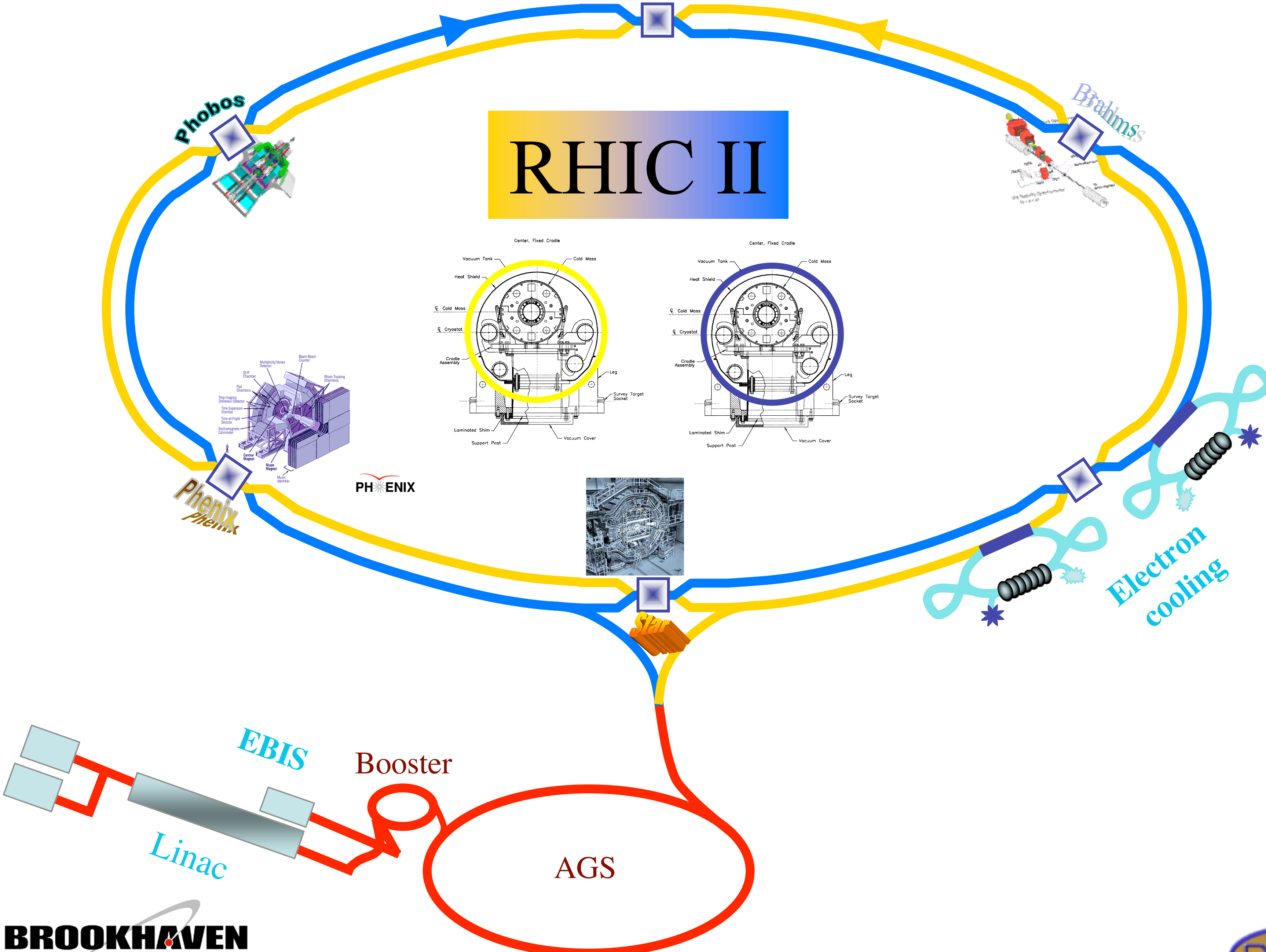
- **ERL prototype**
  - Goals & Parameters
- **Step by Step tests**
  - SRF gun, SRF cavity, beam dump
  - Future steps:
    - return loop for ERL - single and double turns
    - beam stability and feedbacks tests
- **ERL modes of operation**
  - CW and test modes for Navy and DoE
  - Test relevant for the eRHIC concept
- **Conclusion**

Goals for ERL R&D program at BNL

- Test the key components of the RHIC II electron cooler:
  - Au-Au luminosity ➙ 7×10^{27} $cm^{-2}sec^{-1}$, 10- fold boost in p-p luminosity
- Test the key components of the High Current Energy Recovery Linac based solely on SRF technology
  - 703.75 MHz **SRF gun** test with 500 mA
  - high current 5-cell **SRF linac** test with HOM absorbers
    - Single turn - 500 mA
    - Two turns - 1 A…..
  - test the beam current stability criteria for CW beam currents ~ 1 A
- Test the key components for future linac-ring e-p and e-ion collider eRHIC with luminosity of 10^{34} $cm^{-2}sec^{-1}$ per nucleon
  - 10-25 GeV SRF ERL for eRHIC
  - SRF ERL based an FEL -driver for high current polarized electron gun
- Test the attainable ranges of electron beam parameters in SRF ERL

Beam parameters

ERL	e-Cooler	Prototype
ERL circumference [m]	~ 120	~ 20
Number of passes	1	1 to 2
Beam rep-rate [MHz]	9.38 -28.15	**9.38 – 351.875**
for tuning		1 Hz – 1 kHz
Beam energy [MeV]	54.677	20 - 40
Electrons per bunch (max)	10^{11}	10^{11}
Normalized emittance [□m rad]	~ 50	< 50
RMS Bunch length [m]	0.03 – 0.2	0.05
Charge per bunch [nC]	1.6 – 16	**1.3 – 20**
Average e-beam current [A]	0.15 – 0.45	0.02 – 0.5
Efficiency of energy recovery	99.9…%	> 99.95%
Efficiency of current recovery	99.999….%	> 99.9995%



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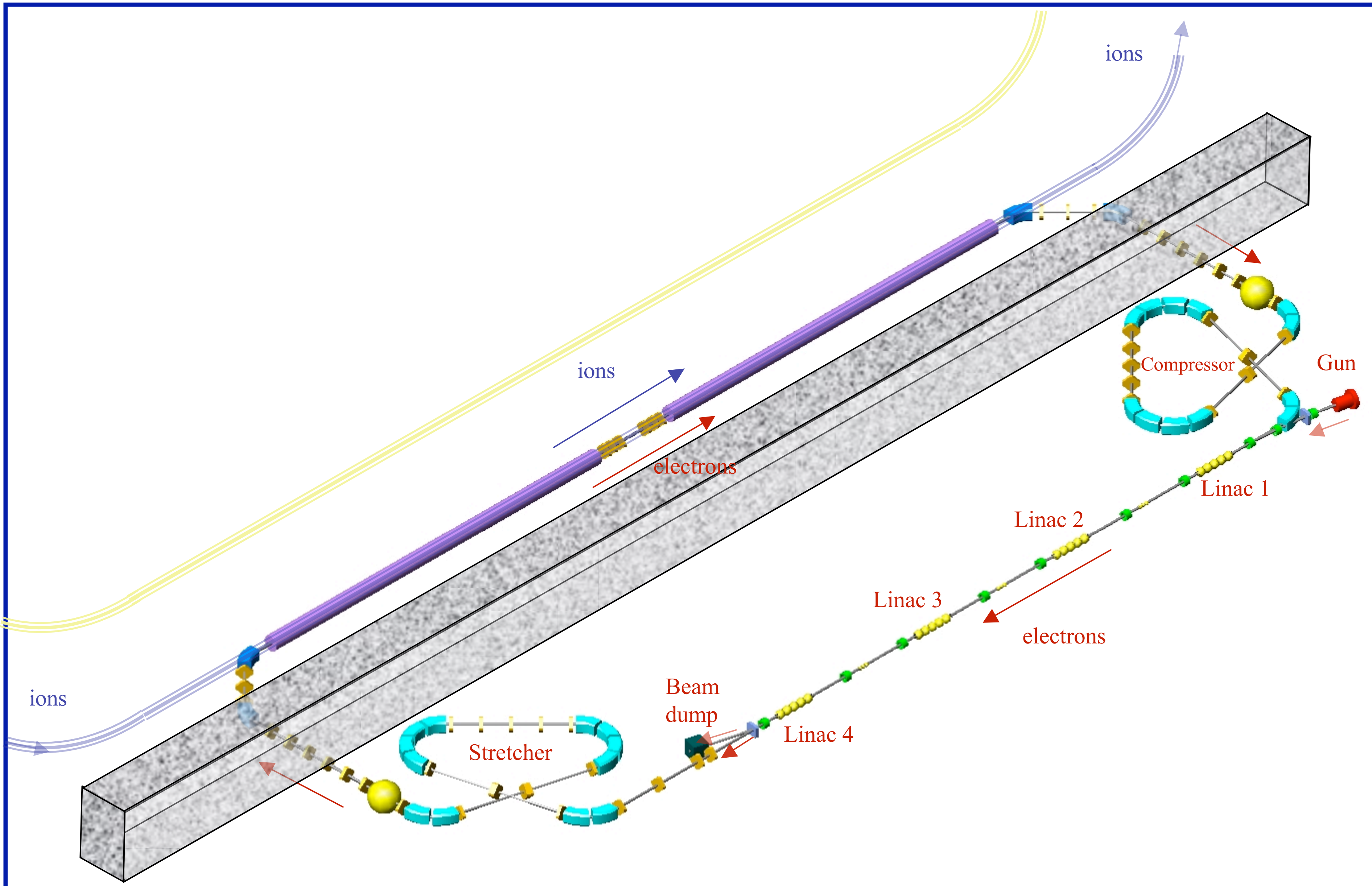

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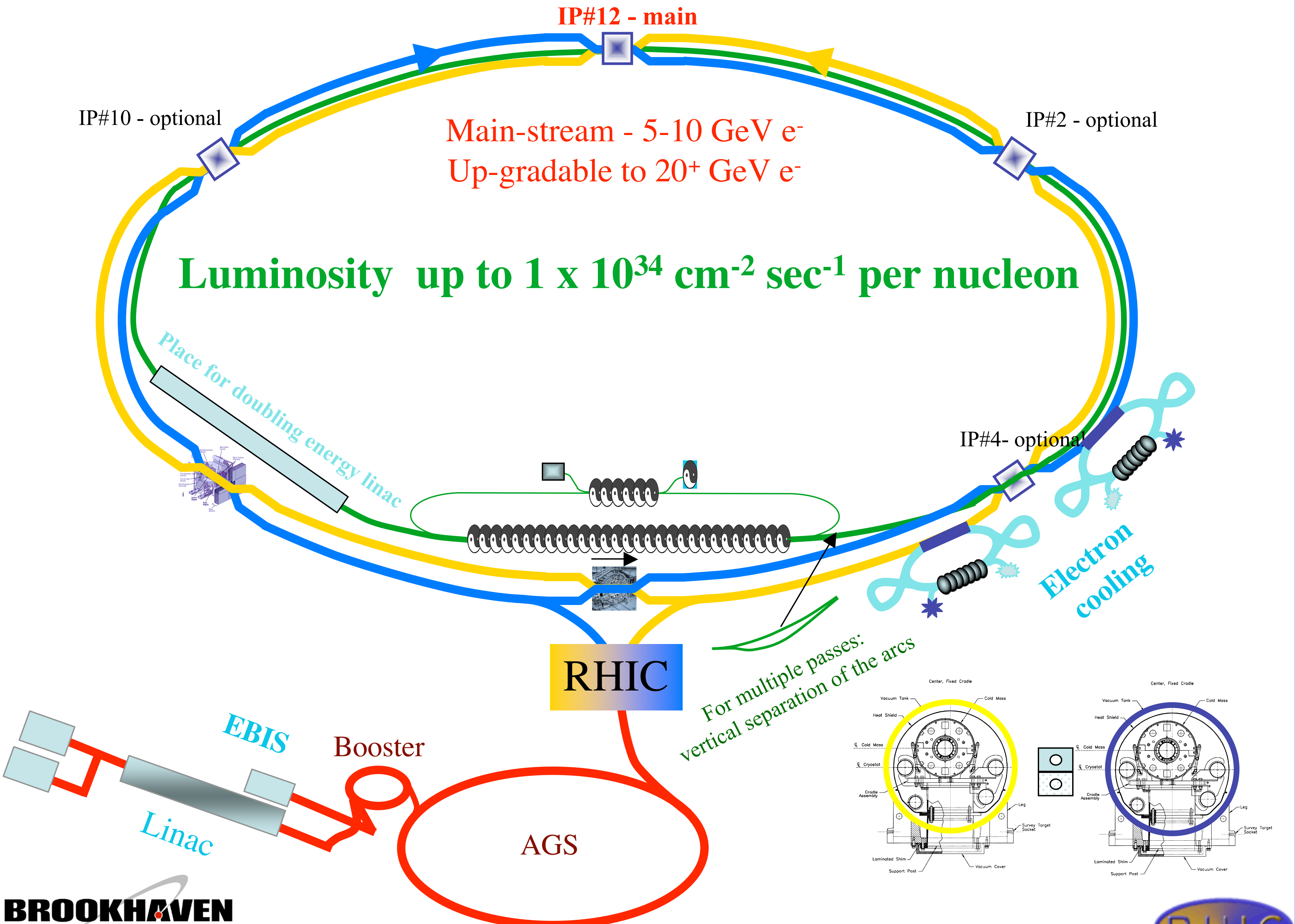

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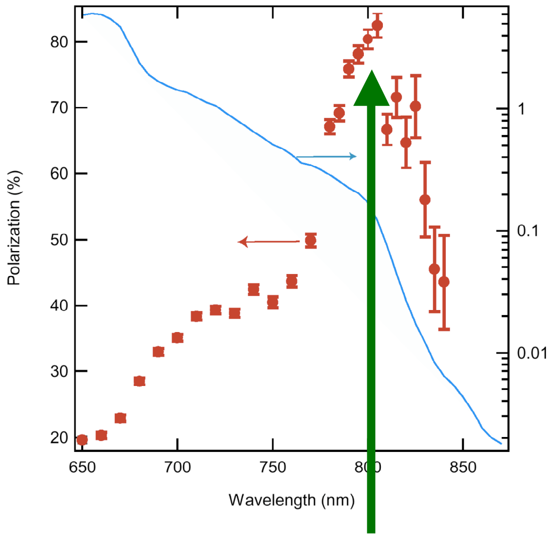
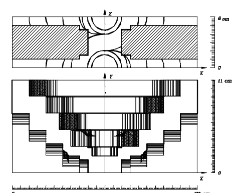
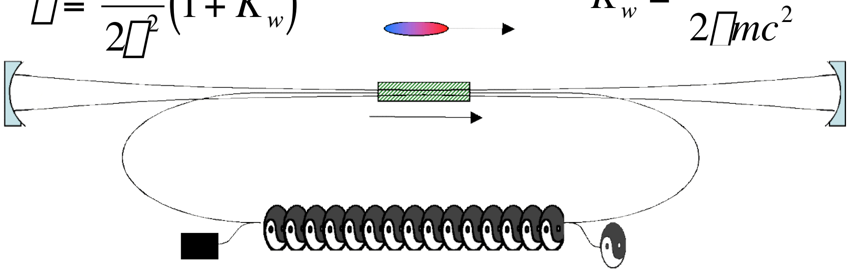
Polarized electron gun needs an FEL driver





FEL for polarized gun:

$$\lambda = \frac{\lambda_w}{2\gamma^2}\left(1 + K_w^2\right) \qquad K_w = \frac{eB_w\lambda_w}{2\pi mc^2}$$



Gun requrements			
Wavelength [nm]		815 ± 15	
Polarization		circular (left/right)	
Laser power [W]		**2,283**	for 0.03% QE
Mode of operation		CW	
Rep-rate		28.15 MHz	
Energy per pulse [μJ]		17 - 844	
μ-Pulse duration [psec]		100 - 200	
Peak power [kW]		170 – 8,440	
Stability	Pulse-to-pulse	< 0.1%	
	Long term	< 1%	

Electron beam	
Energy [MeV]	**160**
Beam current (mA)	**5 → *560***
Beam Power (MW)	0.8 → ***90***
FEL ext. efficiency	up to 0.75%
FEL power (kW)	**6 → *670***
Charge/bunch (nC)	0.18 → ***20***
Rep. Rate (MHz)	28.15

Wiggler	
Type	helical with switchable helicity
Length [m]	2 x 0.9
Period, λ_w [cm]	6
Aperture [cm]	1
Wiggler parameter, K_w	1.29 - nominal (tunable within 0-1.5)
Peak magnetic field [T]	0.230 (tunable within 0-0.265)

Laser light	
Wavelength, λ [nm]	815, nominal, (tunable within 400 – 1000 nm
Chirp [nm/psec]	5
Polarization	**100% circular (left/right)**
Spot-size in FEL[cm^2]	0.0020
that the mirror [cm^2]	2.08
μ-Pulse duration [psec]	5 (chirped)

Optical cavity	
Length [m]	31.8926
Radius of curvature [m]	15.962
Rayleigh range [m]	0.5
Out-coupling	10%

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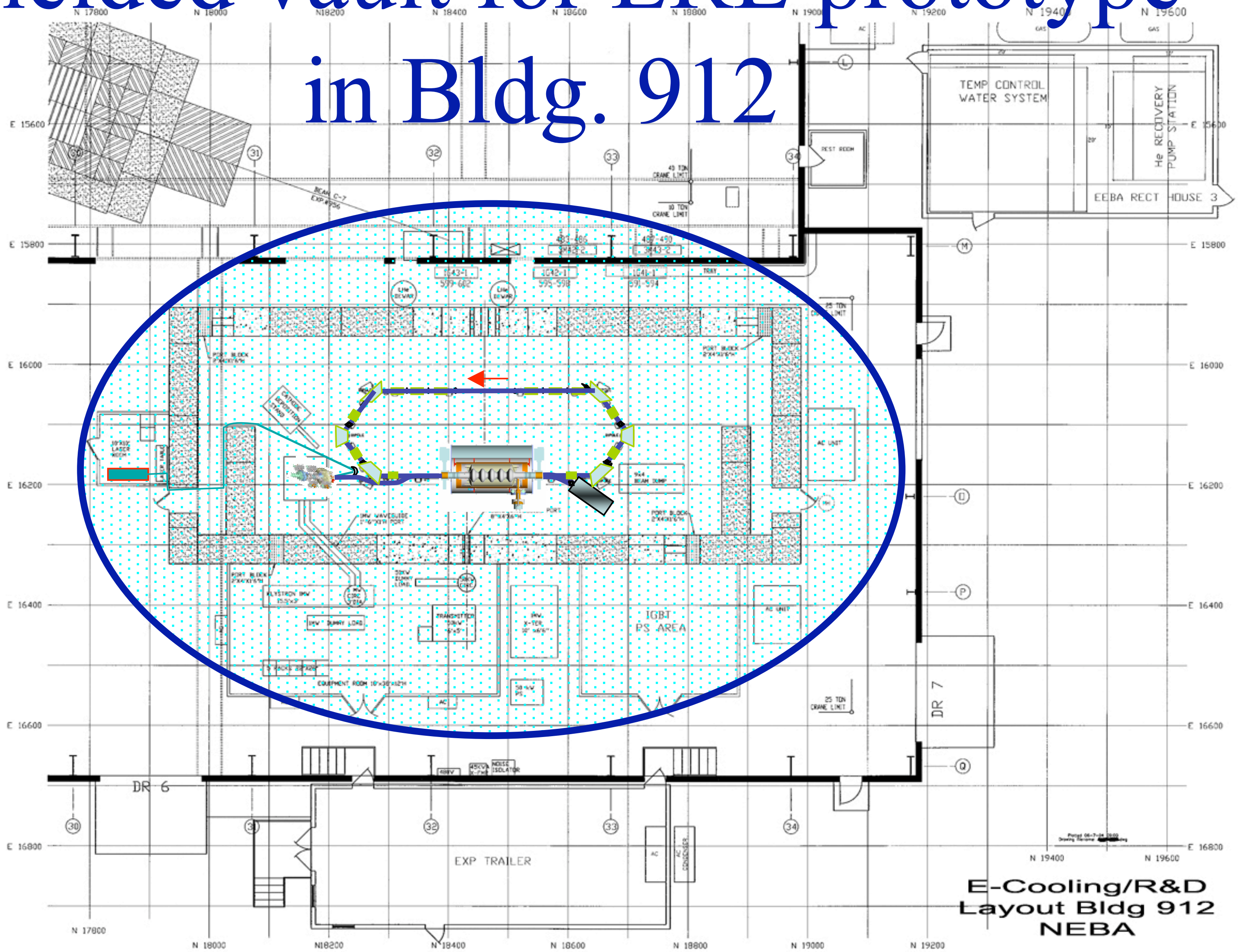
Shielded vault for ERL prototype in Bldg. 912



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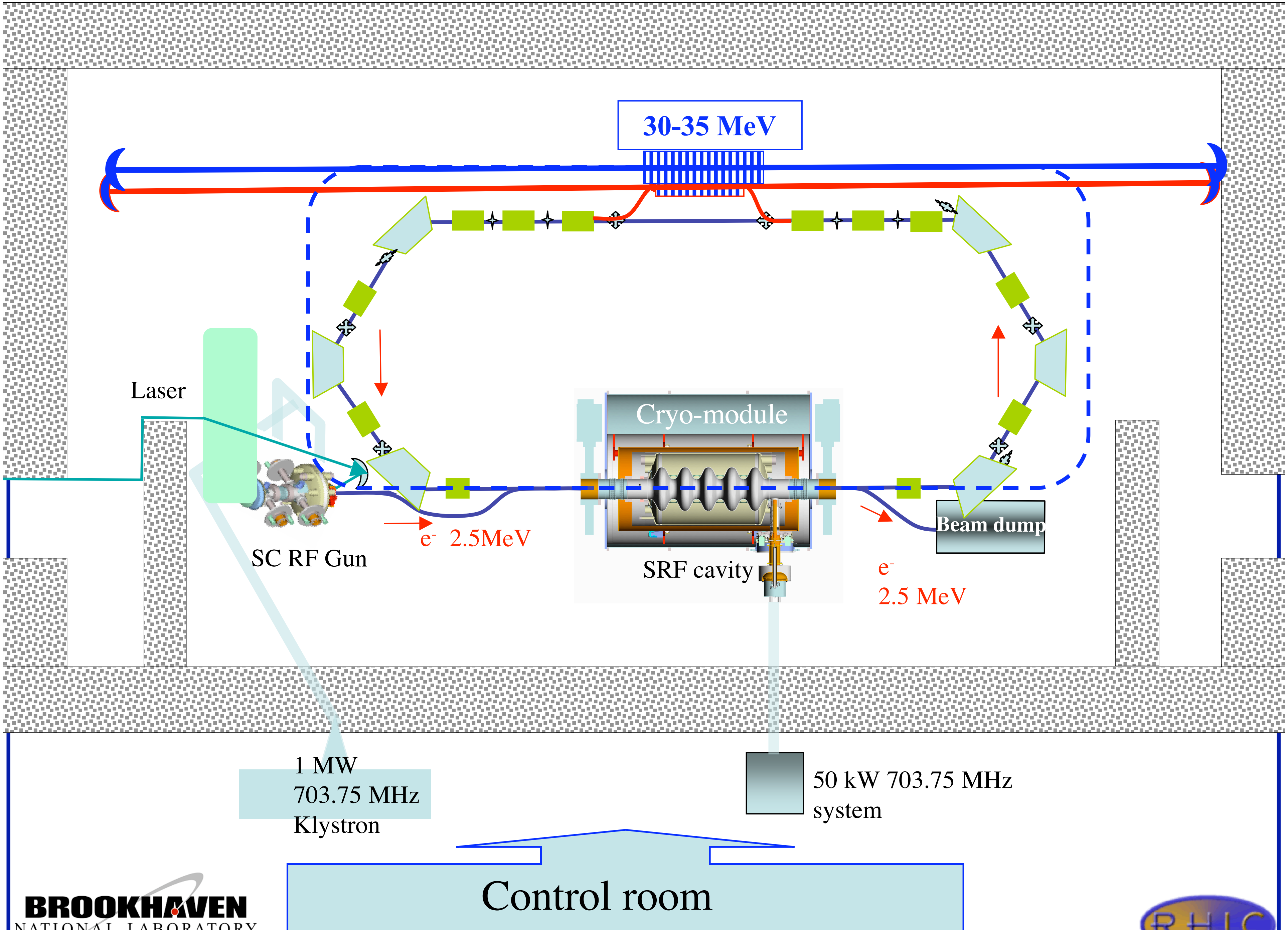
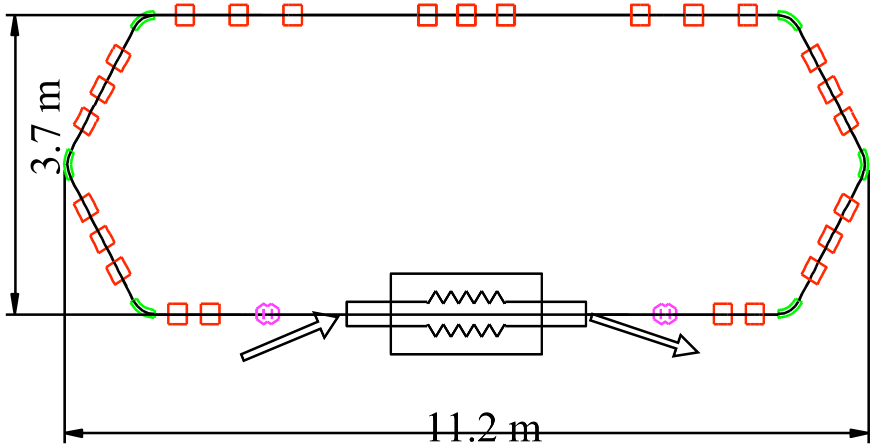
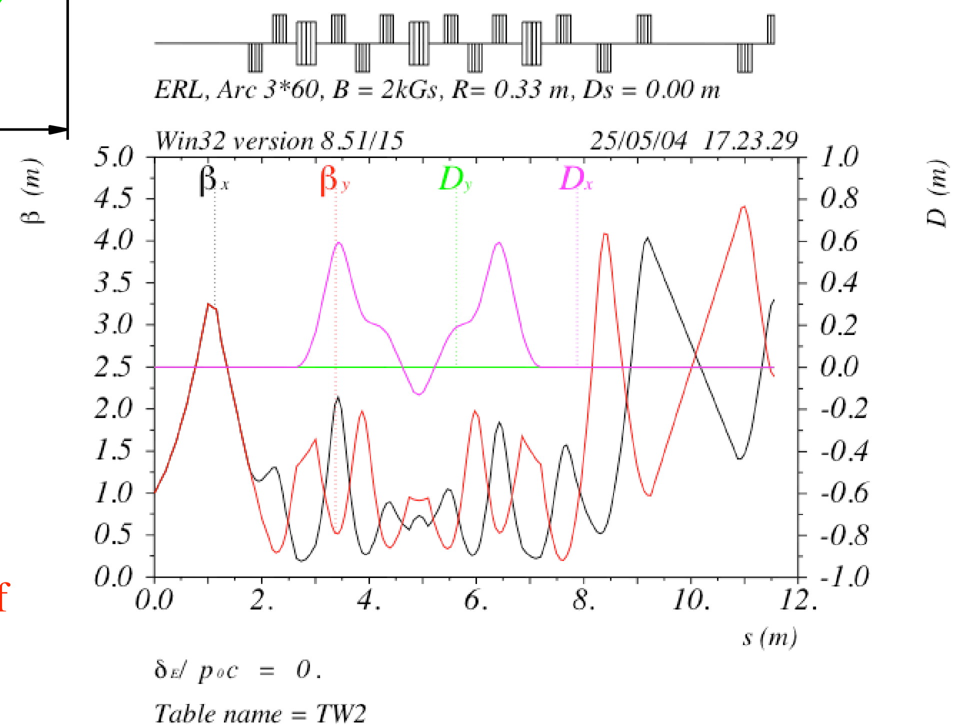

30-35 MeV
Laser
Cryo-module
SC RF Gun
e- 2.5MeV
SRF cavity
Beam dump
e-
2.5 MeV
1 MW
703.75 MHz
Klystron
50 kW 703.75 MHz
system
Control room

ERL Lattice is very flexible



Lattice of ERL has bilateral symmetry: it comprises of six 60^o dipole magnets, twenty five quadrupoles and two solenoids



Lattice functions for the case of zero longitudinal dispersion: Figure shows β- and *D* - functions only for a half of ERL lattice from the end of the linac till the middle of the straight section. The functions for the remaining part are a simple mirror image of the figure.

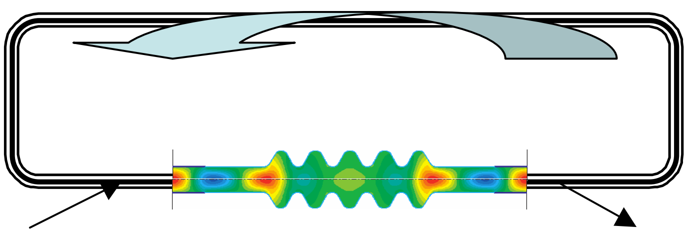
Main features of ERL

- Control of M12 for studying the transverse stability limits in both horizontal and vertical directions
- Control of longitudinal compaction factor for studying longitudinal dynamics

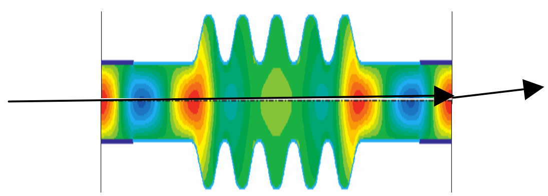
$$m_{12} = \sqrt{\beta_{1x}\beta_{2x}}\,\sin \Delta\psi_x$$

$$m_{34} = \sqrt{\beta_{1y}\beta_{2y}}\,\sin \Delta\psi_y$$

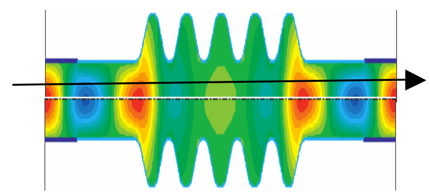
$$m_{56} = \oint \frac{D}{\rho}\, ds$$



$$\begin{pmatrix} x \\ x' \\ y \\ y' \\ c\Delta t \\ \Delta E/E \end{pmatrix}_{s2} = \begin{pmatrix} m11 & \mathbf{m12} & \dots & \dots. & \dots & \eta_x \\ m21 & m22 & \dots & \dots & \dots & \eta_x' \\ \dots & \dots & m33 & \mathbf{m34} & \dots & \eta_y \\ \dots & \dots & m43 & m44 & \dots & \eta_y' \\ \dots & \dots & \dots & \dots & m55 & \mathbf{m56} \\ \dots & \dots & \dots & \dots & \dots & m66 \end{pmatrix} \cdot \begin{pmatrix} x \\ x' \\ y \\ y' \\ c\Delta t \\ \Delta E/E \end{pmatrix}_{s1}$$



$$\begin{pmatrix} x \\ x' \end{pmatrix}_{return} = \begin{pmatrix} m11 & \mathbf{m12} \\ m21 & m22 \end{pmatrix} \cdot \begin{pmatrix} 0 \\ x' \end{pmatrix}_{comming}$$



Excitation process of transverse HOM

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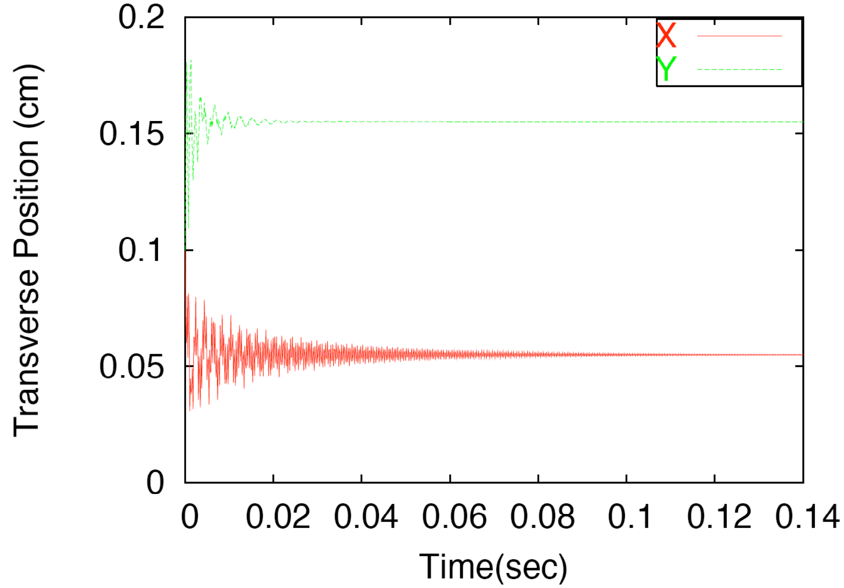
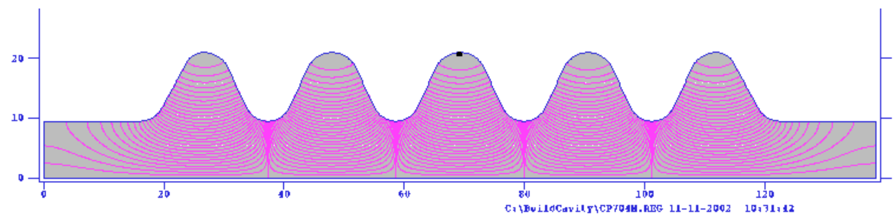
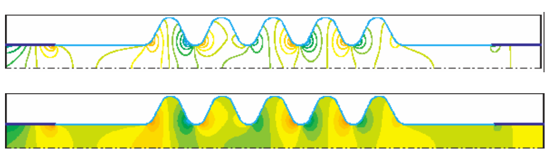
Stability of ERL

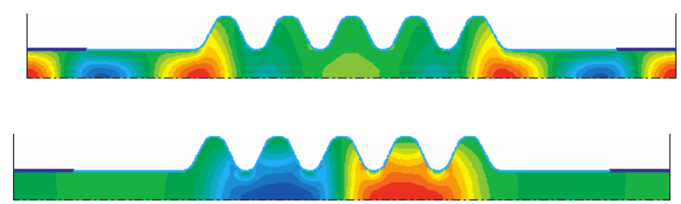
(R. Calaga)

- TDBBU, MatTBBU give for ERL with this cavity stability limit: currents up to ~1.8 A (1,800 mA !) for a proper lattice
- We plan to increase M12 in order to measure the TBBU and to compare with predictions by TBBU









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Conclusions:

- The prototype ERL will demonstrate the main parameters of the e-beam required for e-cooling
- The prototype will also serve as a test bed for studying issues relevant for very high current ERLs and high power FELs *(with some additional support)*
- Basic scheme is well understood
- Many more calculations and simulations are under way

Parameters of FEL for eRHIC's polarized gun *and its potential*

Electron beam

• **Energy [MeV]**	**160**
• **Beam current (mA)**	**5** → *560*
• Beam Power (MW)	**0.8** → *90*
• FEL ext. efficiency	up to **0.75%**
• **FEL power (kW)**	**6** → *670*
• Charge/bunch (nC)	0.**180** → *20*
• Rep. Rate (MHz)	28.15

Wiggler

• Type	helical with switchable helicity
• Length [m]	2 x 0.9
• Period, λ_w [cm]	6
• Aperture [cm]	1
• Wiggler parameter, K_w	0-1.5

Laser light

• Wavelength, λ [nm]	815
(tunable within 400 – 1000 nm)	
• Chirp [nm/psec]	5
• Polarization circular (left/right)	100%
• Spot-size in FEL[cm^2]	0.0020
• that the mirror [cm^2]	2.08
• □-Pulse duration [psec]	5

Optical cavity

Length [m]	31.8926
• Radius of curvature [m]	15.962
• Rayleigh range [m]	0.5
• Outcoupling	10%

Parameters of FEL for ERL prototype

Electron beam

• **Energy [MeV]**	**20** → *40*
• **Wavelength [μm]**	**10** → *2.5*
with micro-wiggler	*(5→ 1)*
• **Beam current (mA)**	**500**
• Beam Power (MW)	**10** → *20*
• FEL ext. efficiency	**1%**
• **FEL power (kW)**	**100** → *200*
• Charge/bunch (nC)	1.3
• Rep. Rate (MHz)	301.88

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